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AD No. 407207  
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JPRS: 17,227

S&T

22 January 1963

CYBERNETICS AND AUTOMATIC CONTROL

by V. A. Trapeznikov

- USSR -

407 207

U. S. DEPARTMENT OF COMMERCE

OFFICE OF TECHNICAL SERVICES

JOINT PUBLICATIONS RESEARCH SERVICE

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Washington 25, D. C.

Price: \$2.60

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CYBERNETICS AND AUTOMATIC CONTROL

- USSR -

Following is a translation of an article by V. A. Trapeznikov, Academician, in the Russian-language periodical Vestnik Akademii Nauk SSSR (Journal of the Academy of Science, USSR), Vol XXXII, No 5, Moscow, May 1962, pages 33-42. First presented as a speech at the Annual Meeting of the Academy of Science of the USSR on 7 February 1962.<sup>7</sup>

During the last few years, cybernetics and the problems connected with it more and more excite the imagination and serve as topics for debates and discussions. The growth of interest in cybernetics has been remarkable. It is a sign of the beginning of a new epoch in science and of the rise and rapid growth of its new divisions linking together fields of knowledge which yesterday still seemed to be widely separated. Cybernetics is the science of control, and control is united purpose of action. We observe the processes of control everywhere, in living organisms as well as in the automatic machines which we create and in the society in which we live.

But only a comparatively short time ago did we grasp very important concept of a unity of laws, to which the control processes are subordinate, no matter where they are found, be they

in the nervous system of an animal or of man, in a computing machine, in the control mechanisms of automatic machines, or in the economic structures of modern society. This idea was the basis for cybernetics.

Control did not exist before the emergence of life, but arose with its origin. This distinctive characteristic is a common feature of living organisms. Everywhere, where life is met, we find that it is associated with control processes. And everywhere, where we meet control processes in nature, we without exception also meet the phenomenon of life.

With the alternation of countless generations, the forms of life were perfected, the organisms became more complex, the level of vital activity increased and, finally, in the form of human life, came to know itself. One of the most important results of this recognition was the creation of artificial control systems, the offsprings of human genius. The first automatic machines in the history of the earth appeared. Systems in which united purpose of action was accomplished without direct participation of living organisms were created. But man, the creator of these automatic machines, gave them purpose and forced them to serve his will. The world of automatic machines is closely tied to the world of people. They are his creation and reflection.

The imitation of a man's or an animal's activities was the starting point for the creation of the first, comparatively primitive, automatic control systems. As late as the XVIII century,

they even tried to give the automatic machines a superficial resemblance to living organisms. Without a doubt, priority in the area of the basic principles of control belong to nature. And, nonetheless, the appearance of the first automatic machines was the portent of a new era. The crux of the matter lies not only in the practical benefits of automatic machines, but also in consequences of a scientific nature. The primitive control systems created by man could be thoroughly studied and could be "picked to pieces." Man was then able to study these "cells" of the world of automatic machines and these simplest of concepts, the knowledge of which is necessary for the creation of a theory and the emergence of the laws of control. Only by following this method is it possible to study the complicated relationships which exist in the interdependent systems of control characteristic of a living organism. That is why the development of the theory of control was based on technical achievements. Automatic machines gave rise to cybernetics. And up to the present time this is why its division which is concerned with the theories of control in technical systems - technical cybernetics - is the furthest advanced. It is chiefly the area of technical cybernetics which has seen an exceptionally high rate of growth, and not only a growth of ideas and theoretical results, but also the introduction of these ideas into life and practice. In this way, the practical value of cybernetics became apparent before everything else through its technical adaptabilities and applications.

But the development of cybernetics is extremely important for all the sciences which touch upon it. The principle of unified laws of control has, other than a cognitive, also a purely practical value. It permits the checking of various hypotheses concerning the functioning of the nervous system on inanimate models and, at the same time, helps the physiologists to understand its functions. The collaboration of physico-mathematical, technical and biological sciences promises a revolution in biology. The principle of unified laws of control is also invaluable for engineers, because intelligent observation of man's activities and analysis of his physiological and psychological causations give rise to new ideas and new principles of construction for complex automatic machines.

Thus, the process of control is the basic indication of vital activity. [See Note.]

[Note: In order to avoid a misunderstanding, we will note that we do not by any means intend to establish a level of equality between a living organism and an automatic machine, even though in each of them control processes are realized. An automatic machine is a product of the activities of a living being - of man.]

Cybernetics, then, is a complex science which studies control processes over a wide field and appears in connection with manifestations of life in general and the activities of man in particular. Control processes in a cell, in an organism, in the associations of living organisms, in human society, in an

automatic process and in the variegated manifestations of man's intellectual activities are, all of them, areas encompassed by cybernetics.

Of course, we are far from having the thought of trying to expound on the many various tasks of cybernetics and will discuss only one of its divisions - automatic control.

By using scientific achievements, man is in ever-greater measure conquering the forces of nature. The development of atomic energy has acquired tremendous importance in our day. Without a doubt, Soviet science will also solve the problem of controlled thermonuclear reactions. However, there is no doubt that this powerful force can be curbed only with the help of automatic control. Indeed, even the atomic reactors now operating cannot function without automatic control. More than that, it can be asserted that all the modern, highly-efficient processes require the use of automatic control.

Automatic control, to an ever-increasing extent, is taking over in many varying branches of the national economy. Each day brings news of the activation of automatic machinery in metallurgy, chemistry, machine construction, energetics and mining.

Automatic control systems have escaped the confines of the earth, they have reached the moon, they extend their potential far out into space. Even the successful launchings of artificial earth satellites and space vehicles would be unthinkable without the use of highly perfected systems for automation in them.

We all know how much importance is attached in the Program of the Party to the tasks of automation as one of the main lines for technical progress to provide a radical increase in productivity and an improvement in the conditions of labor.

The tasks for widespread automation of the national economy formulated by the Program of the CPSU require the accomplishment of a wide range of scientific research. A number of unsolved problems is holding back automation. Many processes and machines are not mechanized and not prepared for automation. We still are not able to control many quantities, have not solved questions concerning the reliability of equipment and the utilization of computers and control machines is difficult not only because of their poor reliability but also because many processes which could be made automatic have not been thoroughly studied and are not ready for the use of such machines.

One could talk about a multitude of pressing scientific problems relating to the field of automatic control, but we will stop only on the main, long-range problems having special significance for the development of science and the solution of pressing problems awaiting us in the future.

A control process exists throughout the whole life of an organism and throughout all the functions of an automatized apparatus. Whether visible or invisible, it always consists of three operations - study of the unit to be controlled, planning of the control program and realization of the adopted program. These elements are also

present in the so-called "open" systems, where the feedback closes the circuit through a human. They are also present in animate beings.

Let us follow the control operation through with the simplest example, a thermostat. A thermometer, while measuring the temperature of an unit, studies it. This is the first control operation. The second operation is the planning of the control program. In the case of a thermostat, it is a change of temperature according to a determined program which may be set up by a human or calculated by a computer. The third operation, realization of the program, is maintaining the temperature at a given level by decreasing or increasing the feed of energy into the unit.

Let us return to the first operation of the control process, the study of the unit being controlled. Modern technology is converting from the control of individual apparatuses to the control of complexes; therefore, in the majority of systems, the collection of information for study of its state is carried out with the help of numerous data units which are frequently located at long distances, as, for example, in power systems, in space vehicles and other units. For processing information, specialized computing and logic machines have been created which expose disturbances in the normal functioning of processes in correspondence with algorithms previously put in.

Similar mechanisms are beginning more and more to occupy a place in control systems. At this point, many scientific problems

arise in the utilization of the new physical phenomena for control, in the principles for creating highly dependable systems, in the working out of programs for rational collection and processing of information providing a maximum of useful information when using the most simplified system, and so forth.

Now we are on the threshold of creating remarkable machines for studying the unit to be controlled and machines into which an algorithm, or a calculated formula, has not been put in beforehand. I am speaking of learning and self-teaching mechanisms capable of determining the state of a system over a long period of time according to a series of indicators which man is either not quite capable of perceiving, or perceives only subconsciously. This will permit carrying out of the control process when incomplete information is available and at the same time simplifying its collection.

One of the more interesting learning processes is the recognition of visual forms. Form is the conception which a person relates to a definite shape, is able to recognize and relates to a particular group, even though he, perhaps, has never before met the given representative of the group. Thus, for instance, the letter "A" is a form, because the inscription of this letter, written in varying styles of handwriting, is perceived as a letter "A". Other examples of form are the concepts of "a masculine portrait", "the cipher 1" and so forth.

Imitation of the learning process is one of the important

problems in cybernetics, especially if one keeps in mind the long-range drawing together of the functions of a machine and the functions of the human brain.

In this connection, many works which deal with mechanisms for the recognition of forms, the so-called "perceptrons", have appeared in world literature during the past few years.

How does the learning process take place? One can imagine that a teacher, who already is able to distinguish these forms, works out a system of symbols (an original program) with which it is possible to recognize letters or other forms and teaches this program to a student. Such an approach is being imitated in many machines now under development for reading printed or written letters. In this case, the learning process comes to a working out of a system of symbols for inclusion into a well-conceived program.

There exists, however, another approach to the learning process which is much more interesting from the viewpoint of imitating it in a machine. The teacher, who does not attempt to work out a system of symbols and to explain how to distinguish letters, shows each of the students several letters and names them. Very quickly, the students begin to identify the letters with confidence, even though they were not taught their symbols or programs for recognizing them.

One of the employees of the Institute for Automation and Telemechanics (E.M. Braverman) has put forth a hypothesis which

he has called the hypothesis of compactness. This hypothesis has permitted the explanation of the learning process and its reproduction artificially, even though, naturally, it is not absolutely sure that the learning process occurs exactly in this manner in the human brain.

Let us picture a photographic field, that is, a plane surface which has been divided into cells and filled with photo-cells. An image is projected on the photographic field and light falls on a part of the photo-cells which also have been sensitized. Let us further imagine a polydimensional space having as many coordinate axes as there are photo-cells contained in our field. Each photo-cell can only be sensitized or non-sensitized; therefore, its state can be characterized on each axis by two points, having point "1" which corresponds to the sensitized and point "0" which corresponds to the non-sensitized states. During projection onto the photographic field of some kind of image, quite definite photo-cells turn out to have been sensitized, and the state of the whole photographic field can be represented by one point in the space described above and named the receptor field. This point is the apex of a single polydimensional cube constructed on the coordinate axes.

Every image projected onto the photographic field, for example each letter "A", has its own corresponding point in the receptor field. All the letters "A" written in different styles of handwriting have one corresponding number and one group of

points in this field occupying some area, and all the letters "B" another number and occupying another area of space. If the areas which correspond to the various forms do not intersect, then the forms are different. It is possible to suggest that in the human brain areas corresponding to one or another shape are formed in the receptor field by some means.

The hypothesis of compactness is formulated as follows: A person receives a number of different visual sensations as a united form if the number of points which corresponds to this sensation in the receptor field is, in a sense, a compact number (Here the term "compact number" has a somewhat different meaning than that found in mathematical analysis.)

Corresponding to such a hypothesis, the task of learning comes down to the insertion of surfaces separating one area from another in the polydimensional space. This task can be performed by the machine, and then the machine acquires the ability to distinguish forms.

The learning process of the machine takes the following course: The machine is "shown" images, for example the letters "A" and "B", and is informed by a pre-arranged code of the kind of letters they are. Then the machine computes and memorizes the position of the surface which separates the "A" and "B" areas in the receptor field. According to the number of the images shown which are written in varying styles of handwriting, the machine makes the position of this surface more and more

precise and at the same time continually teaches itself. When, after this, the machine is shown an image and is "asked" by the pre-arranged code what letter it is, the machine determines on what side of the dividing surface the point is which represents the image shown and, depending on this, gives the answer.

This type of machine is suitable for learning to recognize the most varying forms, because their construction and program do not contain symbols of a specific form and are guided only by a hypothesis that the points which correspond to every form are available in the compact area.

The mentioned idea was made the basis for a program developed in our institute and realized on the data machines of the Computing Center of the Academy of Sciences of the USSR and of several other organisations. The first experiments provided very good results. At first, experiments were set up for teaching machines to recognize five ciphers. The program did not contain information on the ciphers or symbols by which they could be identified; that is, this program was not suitable for recognising ciphers, but for letters, geometric figures and so forth.

We prepared 200 inscriptions of each cipher written in various styles of handwriting, of which 40 forms of each cipher were used for learning, and the remaining 160 forms were applied for checking how well the machine had learned to recognize. During the learning operation, the machine was shown the 40 picked ciphers and informed by the pre-arranged code what cipher

it was. Then it was shown the remaining 160 versions of each cipher which had not been considered previously by the machine and the machine was required to recognize them. Out of 800 attempts, the machine was mistaken only in four cases.

The success of the first experiments inspired our co-workers, and experiments of a wider scope were set up during which the machine successfully learned to recognize all ten ciphers on the basis of very little learning material. At the present time, a broad series of experiments of this type is projected. Experiments are planned for teaching machines to recognize all letters of the alphabet and even portraits. Simultaneously, experiments with animals are being prepared in one of the laboratories of the Academy of Medical Science to ascertain the plausibility of the hypothesis of compactness.

The possibility of teaching machines a recognition process opens unusual opportunities for automation. It may be that it will turn out to be advantageous to construct monotype machines for analyzing various situations, and later to specialize these machines by means of learning. The experiments described show that the idea of such a type is realistic.

It is already clear that in the near future machines will be successfully taught not only to recognize forms, but also more complicated processes. Turning to the future, we see surprising machines which have been taught to replace man in performing the most delicate operations. One can conceive of machines which

learn to recognize by the sound of an apparatus which is operating just where an irregularity has occurred, or to make a diagnosis by listening to the beating of a heart.

Of course, a long and tortuous path will have to be traveled from the first experiments until the realization of these ideas, but the success already achieved instills confidence that the approach to the construction of the machines - at first of one operation and then learning other operations - is feasible, and herein lies one of the most important directions of automation in the future.

I will turn to the second operation of the control process - to the working out of a plan or program of control. In living nature, a control plan is not always developed by each individual independently. Basically, it is produced in the process of development of a species and is transmitted to the individual through inheritance in the form of reflex actions and the presence of individual parameters, such as temperature, concentrations of solutions and others, in the different conditions of a living organism.

In automatic control systems, the general plan is always set up by a human, but the degree of detailing of this plan can be different. The process routine (control program) is set up in every detail by a human in the overwhelming majority of modern mechanisms. In automatic lathes, the program may be realized with the help of mechanical connectors, or by means of instructions

on a program tape. In other cases, the process parameters (temperature, pressure and so on) are set up by a technologist in the form of instructions and realized either by an operator or an automatic regulator.

However, in the last analysis, we are not interested in the temperature or another parameter of one or another point of the system, but in the overall result of the operation, such as the quality of the finished product, economy and productivity of the mechanism, or some other index.

The requirement for higher economy of a process compels a search for optimal criteria providing the most suitable operational routine for an aggregate, shop, factory and, finally, for a whole branch of industry. In the presence of such a complexity of control problems, man has proved to be incapable of comprehending all the data needed for making the best decisions. This problem can be solved only with the aid of computers.

At the present time, the technology of automatic control is entering into a new period characterized by the automation of the development of a control plan on the basis of more and more general criteria.

Two fundamentally different methods have been planned for determining the best control plan. The first method is the "rigid" plan, whereby a computer, after processing the collected information and ascertaining the state of the system, determines the necessary work routines according to the specified correlations.

However, this method requires not only a detailed mathematical description of the process, which sometimes proves to be most difficult, but also a knowledge of all the operating conditions of the system which can, in the course of time, change. Therefore, another method was planned and a theory for a control system developed which includes automatic adaptation to changing conditions.

It is well-known that living organisms possess an extraordinarily high level of adaptation. What is the secret of this remarkable capability? It has been proved that the main characteristics of adaptation are, on the one hand, a structural flexibility of the organism and, on the other, a capacity to change the unified purpose of this structure.

These peculiarities are also beginning to be utilized in the field of automation, and during the past few years we have been witnesses of a stubborn and urgent attempt to increase the structural flexibility of control mechanisms. New elements, reliable and small, which can be assembled by various methods in large quantities, have emerged. New plans are appearing for crude elementary units which, in a general way, are modeled on the behavior of nerve cells, the so-called nerve models. And, finally, new types of arrangements and mechanisms are appearing modeled on the construction of nerve fibers, the nerve clusters.

But there is still very little of one structural quality. Mechanisms must be provided with a capability for a unified

purpose of change and adaptability.

The most general aspect of the processes of adaptation is search. In the search process, trials, experiments and investigations are made. An analysis of their results permits the finding of methods for rational adaptation. Now automatic search systems utilizing a method of "trial and error" are beginning to develop. This type of system is new in technology, but for nature search is not a new method at all. The mechanism of natural selection consists basically of the fact that from the different species of living organisms formed in nature (they can be considered as a type of "trial"), only the most adaptable survive. They transmit to their descendants their own specific traits providing a great capacity for survival. As a result, nature has succeeded in forming complex and highly-developed species of living creatures by modifying billions of organisms.

A question has evolved. Is it possible after artificially accelerating search and rationalizing its methods to obtain new types of automatic machines? This idea is being embodied in new research, particularly in a system of automatic synthesis which has been developed in the Institute of Automation and Telemechanics. In this system, an automatic optimal selector, while trying various versions, changes the parameters, characteristics and even the structure of the control mechanism in such a way that the automatic control system, which they want to perfect or even to synthesise anew, will acquire the most advantageous properties.

Such optimal selectors, and some of them already have been put into serial production, will be applied in the most varying areas of planning and scientific research. Undoubtedly, we are witnessing the birth and development of very interesting ideas which will permit us to entrust to automatic mechanisms still more of the functions connected with the intellectual activities of man.

Other new types of optimal selector mechanisms providing flexible control plans which adapt to changing conditions are based on the automatic search principle. The theory and the principles for their functioning were developed in our institute. Mechanisms created on their base have been introduced into industry and already are supporting optimal work schedules for metallurgical furnaces, radio transmitters and other installations and are having a substantial economic effect.

However, there is in prospect a great deal of work directed toward increasing the effectiveness of search mechanisms and creating the principles for building them.

It is appropriate here to touch on a problem which often arises — Can a machine perform functions which have not been previously set up in it by the builder? This can be answered affirmatively. Indeed, the builder of the system under discussion does not set up a pattern of operation needed for one or another use of the system. It is enough for the constructor to provide the system a much more general property, the capability of perfecting

and learning, and to set up overall criteria which evaluate the results of its operations (for example, speed of operation). While realizing this capability, the automatic machine will be able to work out the best structure for the system and the pattern of operation by itself, which in a number of cases turn out unexpectedly even for the builder himself. Therefore, we can anticipate the creation of systems which automatically perfect their own structure and at the same time provide an evolutionary change which to some degree resembles the process of evolution in living forms. In this area, without a doubt, we may expect the most interesting scientific breakthroughs.

I will now turn to the third control process, the realization of the adopted plan.

The realization of a control plan in animal life, particularly the maintenance of required values - "selection" in the terminology of the physiologists - is one of the most important functions of control in living organisms.

Compatibly with the technical mechanisms, the problem consists of setting up the selected operating routine in the unit to be controlled as functionally and exactly as possible.

In a number of units, the realization of the adopted plan (programs) is effected by sequential systems and regulating mechanisms which have already been widely introduced. However, many years of theoretical and experimental research would be required to modernise them.

During the past few years, ever higher demands have been placed on similar mechanisms as to precision and high-speed operations. And then the limitations (of power potential, tolerable rate of acceleration and so forth) always present in operating systems became clearly apparent.

As soon as the limiting influences were brought under investigation, it became clear that they, namely, also determine the maximum attainable indexes for control quality and advantageous structure for the controlling mechanisms.

In this connection, there arose the concept of optimal control which achieves the greatest effectiveness by means of the maximum exploitation of the power, endurance and other resources of the system being controlled.

A number of fundamental ideas were originated in our institute. Their development has led to the fact that the theory of optimal control now presents, in its own right, a complete field of science with a literature containing hundreds of scientific publications.

The principles of optimal control have become widespread in practice. They permit the creation of new automatic regulators, sequential systems and many other technical mechanisms, and the attainment of substantial progress on their basic points.

The technical problems connected with the building of optimal control systems led to the formulation of mathematical problems which were successfully solved by the Academician L. S. Pontryagin

and his co-workers and was an important contribution to the calculation of versions.

Up until recently, the technical, as well as the mathematical, problems of optimal control were developed to conform to the control problems of systems with fixed parameters. However, a large number of the technical systems are systems with differentiated parameters, inasmuch as many productive processes are developed not only in time, but also in space and for them the space and time change in the states of the systems being controlled is very essential.

Theoretical research originated and performed in our institute has permitted the solution of important problems of this type and the crystallizing of Pontryagin's principle of a maximum on the control systems by units with differentiated parameters. One may take as an example the optimal control system used for the continuous furnace for heating blanks being rolled which was developed by the Institute at the Magnitogorsk Combine.

A feature of this system is that for the first time in automatic control technology the control signals are formed not in response to the limiting factors of the system being controlled, but is determined by the character of the distribution of the unit's states in space; that is, they are not functions, but functionals of the state of the unit being controlled. Such a structure for a control system is new in principle and very general, because it will permit the realization of optimal control for many different productive and other types of processes (such as the processing

of free-flowing materials, the processes for obtaining pig iron in blast furnaces and so on) and to achieve a high level of effectiveness as compared with existing systems.

There are reasons to believe that some living organisms exist in correspondence with the principles of optimal control. The employees of the Institute of Automation and Telemechanics together with biologists and medical specialists will check these suppositions on living animals and, perhaps, on humans.

We had stopped on the subject of automatic control systems which are performing a number of man's functions and even excelling him in these areas. However, it would be incorrect to believe that automatic control machines will completely eliminate man from the control processes. In the majority of cases, modern control systems represent "man and automatic machine" systems, in which man, possessing the most complex and finest technology, continues to play the role of a commander making the final decisions. This arrangement, apparently, will be preserved in the future also, at least up until machines in all respects excel man in his capacity to control.

In complex modern systems, the functions of automatic mechanisms and of the people participating in control processes are closely interwoven. Therefore, it is becoming impossible to solve the problems of control by limiting oneself only to their technical aspect and not considering the psychological and physiological factors connected with man's participation in control processes.

One must not lose sight of the fact that the builder does not have the capability of "synthesizing" the individual psychological and physiological characteristics of man. Although the functional characteristics of man are also subject to a unified purpose of development and change, the operator, nevertheless, enters into the functioning of a control system because he possesses a certain number of relatively stable virtues. Therefore, the fundamental task in building such systems consists of profitably utilizing the operator's talents supplemented by technical means. Thereby, man must be assigned such a place and he must be placed into such conditions that his labor will be as meaningful and easy as possible.

Research on the "man and automatic machine" systems is not only theoretically possible, but also practically necessary. It is a prerequisite for the further development of a number of important control systems.

Such work has also been begun in our institute in cooperation with the psychologists and physiologists.

We have considered some highly sophisticated automatic control systems. With each passing year, these systems will perform much more complex functions and, in this way, the technological problems will become more closely involved with the problems of the other scientific fields. In this area, the closest cooperation with mathematicians, physicists, chemists, physiologists and psychologists will be mandatory.

The problem of automatic control, without a doubt, will be

the center of crystallization for many branches of science. Automatic control is like a tree standing solidly in the earth and nourished by the sap of urgent practical problems of automation and by the departure point into the area of the most intricate problems of the higher nervous activity of man. It is in this area that we may expect exceptionally interesting and important scientific breakthroughs which will make possible the creation of a highly perfected Communist society.

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